Spin Dynamics in Ferromagnetic Microstructures

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My talk will focus on the excitation spectra of confined magnetic systems. In a sense, these types of experiments date from the earliest work on magnetic thin films. For example, standing spin waves in thin films were observed in the late 1950's. Magnetostatic modes were imaged using magneto-optical techniques in the early 1960's. What is new? The dramatic progress in electron beam lithography and other nanofabrication techniques has allowed for the preparation of a wide variety of patterned systems. At lateral dimensions of a few microns or less, the low-order quantized spin-wave modes of these systems begin to acquire some exchange as well as magnetostatic character. A point of particular interest is that the magnetic microstructure of these patterned elements is often inhomogeneous. As a result, it is not possible to take the dispersion relation for a film and describe an ordinary set of quantized modes by simply by imposing a boundary condition. In spite of this complication, a "normal-mode" description is often possible, and in some cases unique excitations emerge that do not exist in continuous films.

The first example I will consider is a magnetic vortex.[1] A common realization of this structure is the intersection of four Néel walls. The magnetization at the intersection of the four walls is forced to point either out or into the plane. The vortex observed in micron-scale disks is topologically equivalent. The magnetization in the bulk of the disk circulates so as to minimize the total magnetostatic energy at the expense of a large exchange energy in the core. It was realized by Thiele in the 1970's that there is a degree of freedom associated with the vortex core itself, which will experience a force if it is displaced relative to the surrounding vector magnetization field.[2] This is equivalent to the Magnus force experienced by a fluid vortex in a flow field. There is a stiffness associated with this force that is extremely small in macroscopic samples but the associated normal mode frequency approaches 1 GHz for vortices less than 500 nm in diameter.

The experiments are implemented using time-resolved Kerr microscopy (TRKM), which was developed in its current form by Freeman and co-workers and is now used by many groups.[3] For the purposes of this talk, it suffices to think of our approach as a means of doing spatially resolved Fourier transform spectroscopy. We study the response of a sample to an ultrafast magnetic field pulse by measuring the Kerr rotation of a time-delayed optical probe pulse. The spatial resolution (FWHM of the focused probe beam) is approximately 500 nm and the effective bandwidth is about 10 GHz. With an excellent signal-to-noise ratio, it is even possible to resolve signals from samples smaller than the probe beam size.

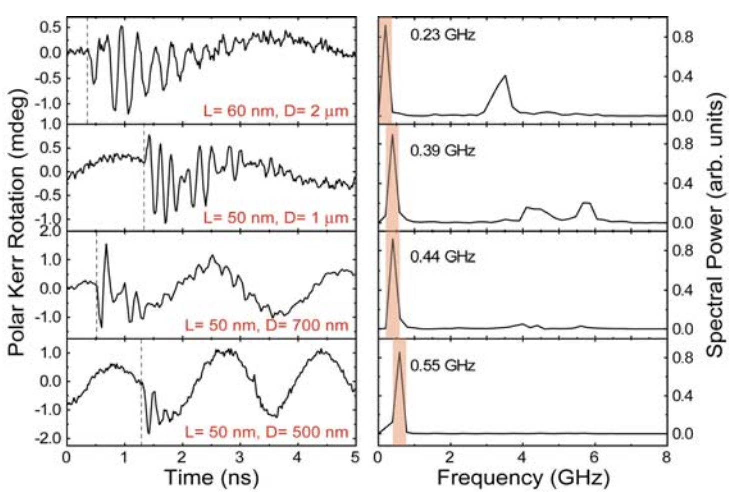

Fig. 1: Time-domain (left) and frequency-domain (right) response for magnetic vortices with diameters from 2 µm down to 500 nm. The dominant low-frequency mode is associated with the gyrotropic motion of the vortex core.

Time-resolved measurements are shown for magnetic vortices of several different diameters in Figure 1. The leading edge of the magnetic field pulse is indicated in each case by the dashed line. As can be seen clearly, the low frequency mode (that I will demonstrate is associated with the gyrotropic motion of the vortex core) shifts to higher frequency as the disk diameter decreases. The higher frequency response is due to magnetostatic modes of the magnetization outside the vortex core. I will discuss some further aspects of these dynamics, including how they evolve in a magnetic field.

The second system that I will address is a ferromagnetic stripe (with a width of 2 microns) in an in-plane magnetic field applied along the short axis of the stripe. In large fields, when the magnetization is saturated, the internal magnetic field is inhomogeneous, and the large gradient near the edges of the stripe leads to localization of spin waves.[4,5] In recent work, we have focused on low magnetic fields, in which the magnetization rotates 90 degrees between the edge of the stripe and its center. Figure 2 shows spectral power images in which power is plotted as a function of position on the stripe (horizontal axis) and frequency (vertical axis). The important aspect of these data is the existence of additional modes which appear at the edges of the stripe at frequencies higher than the fundamental FMR mode observed at the center. This is in contrast to the localized modes, which are observed at lower frequencies than the mode at the center of the wire. I will discuss the origin of these higher-frequency edge modes and how they are associated with the inhomogeneous magnetization distribution.

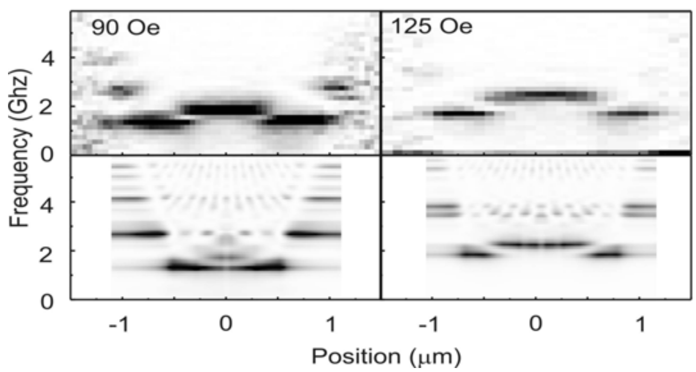

Fig. 2: Spectral power images obtained from a wire with a width of 2 μm in fields of 90 and 125 Oe. Note the modes at higher frequency near the edges of the wire. The lower panels are the results of micromagnetic simulations.

It is worthwhile asking what the limitations are facing this class of experiments and how they might be addressed in the future. Although I would argue that it is possible to extract information from certain types of optical experiments beyond the diffraction limit, the obvious potential of x-ray sources to enhance spatial resolution is already being realized. My uneducated impression is that the timing functions that are so readily implemented in a standard optical pump-probe experiment are somewhat more awkward in the case of a synchrotron. However, as evidenced by the successes of time-resolved PEEM, this impediment is disappearing. An important consequence of enhanced spatial resolution will be access to higher wave-vectors and the possibility of bridging some of the gap that exists between the type of spatially resolved spectroscopy I have discussed here and techniques such as inelastic scattering. To accomplish this we will need to come up with some means to increase the effective bandwidth. I will allude to some possible strategies in my talk.

[1] J. P. Park *et al*, Phys. Rev. B **67**, 020403R (2003); M. Buess ***et al.***, Phys. Rev. Lett. **93***,* 077207 (2004); for BLS experiments, see V. Novosad ***et al.***, Phys. Rev. B **66**, 052407 (2002).
[2] A. A. Thiele, Phys. Rev. Lett. **30**, 230 (1973).
[3] W. K. Hiebert *et al.*, Phys. Rev. Lett. **79**, 1134 (1997); Y. Acremann *et al.*, Science **290**, 492 (2000), and references therein.
[4] J. Jorzick *et al.*, Phys. Rev. Lett. **88**, 047204 (2002).
[5] J. P. Park *et al.,* Phys. Rev. Lett. **89**, 277201 (2002).
[6] C. Bayer *et al.,* Phys. Rev. B **69**, 134401 (2004).
[7] S. B. Choe *et al.*, Science **304**, 420 (2004).